Structural Optimization for Blast Mitigation Using HCA

University of Notre Dame

John Goetz, Huade Tan, Andrés Tovar, John Renaud

UNCLAS: Dist A. Approved for public release

GVSETS

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **07 AUG 2009**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Structural Optimization for Blast Mitigation Using HCA**	5a. CONTRACT NUMBER **W56 HZV-08-C-0236 (SimBRS)**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **John Goetz; Huande Tan; Andres Tovar; John Renaud**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Univeristy of Notre Dame**	8. PERFORMING ORGANIZATION REPORT NUMBER **20151**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **US Army RDECOM-TARDEC 6501 E 11 Mile Rd Warren, MI 48397-5000**	10. SPONSOR/MONITOR’S ACRONYM(S) **TACOM/TARDEC**
	11. SPONSOR/MONITOR’S REPORT NUMBER(S) **20151**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at NDIAs Ground Vehicle Systems Engineering and Technology Symposium (GVSETS), 17 22 August 2009,Troy, Michigan, USA, The original document contains color images.

14. ABSTRACT

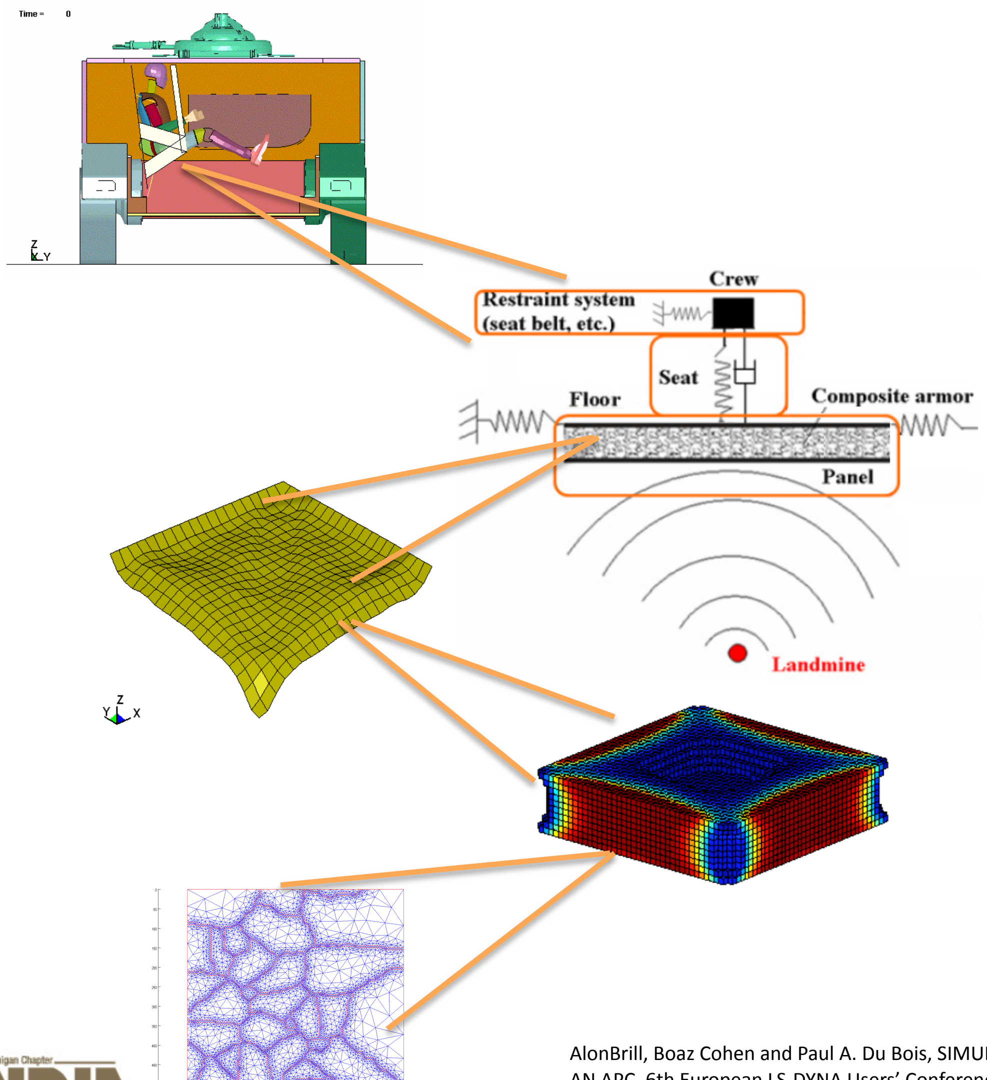
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**21**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Introduction: Design For Blast Mitigation

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION



- The blast mitigation design problem can be reduced sub problems as given
- Each reduction in problem formulation feeds back into the system above
- Design objectives for each sub problem are selected with the overall problem in mind
- Vehicle
  - Design for crew and critical component survivability
- Sub System
  - Design for mechanical isolation between occupant and blast
- Component
  - Design for minimum energy transfer from blast wave
- Sub Component
  - Design for energy dissipation and distribution
- Microstructure
  - Define damage and material parameters for energy absorption

AlonBrill, Boaz Cohen and Paul A. Du Bois, SIMULATION OF A MINE BLAST EFFECT ON THE OCCUPANTS OF AN APC. 6th European LS-DYNA Users' Conference

Introduction: Injury Criterion

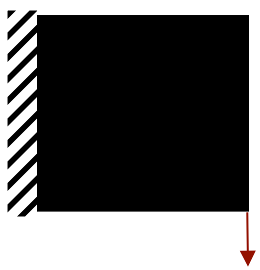
- **Injury criteria of vehicle occupants** due to mechanical input taken **as the design objective** of the vehicle design problem
- Blast impulse is key the metric which drives injury occurrences
- Compressive forces and vertical acceleration taken to be defining factor in injury accumulation

HYBRID III Simulant Response Parameter	Symbol (units)	Assessment Reference Values
Head Injury Criteria Head resultant acceleration	HIC A (G)	750 ~5% risk of brain injury 150 G (2ms)
Neck forward flexion moment Neck rearward extension moment	+ My (N-m) - My (N-m)	190 N-m 57 N-m
Chest resultant acceleration	A (G)	60 G (3ms), 40 G (7ms)
Lumbar spine axial compression force	Fz (N)	3800 N (30ms), 6672 N (0ms)
Lumbar spine flexion moment Lumbar spine extension moment	+ My (N-m) - My (N-m)	1235 N-m 370 N-m
Pelvis vertical acceleration	Az (G)	15, 18, 23 G (low, med, high risk)
Tibia axial compressive force combined with Tibia bending moment	F (N) M (N-m)	F/Fc – M/Mc < 1 where Fc=35,584N and Mc=225N-m
Femur or Tibia axial compression force	Fz (N)	7562 N (10ms), 9074 N (0ms)

Occupant Crash Protection Handbook for Tactical Ground Vehicles 2000
Ala Tabieiand GauravNilakantan, Reduction of Acceleration Induced Injuries from Mine Blasts under Infantry Vehicles University of Cincinnati

HCA Overview: Topology Optimization

- Topology optimization process redistributes material in the design domain to obtain a concept design
- Hybrid Cellular Automata (HCA) algorithm using uniform ***internal energy density*** as a design objective
- Nonlinear transient analysis, utilizing LS-Dyna for finite element analysis (FEA)



$$\min_{t} \sum | S_i - S_i^* |$$
$$\text{s.t.} \quad m_f(t) = M_f^*$$
$$t_{\min} \le t \le t_{\max}$$

Topology optimization to generate concept designs

HCA Overview: Algorithm

- A continuum-based topology optimization
  - First utilized for bone remodeling (Tovar'04)
  - Extend bone remodeling technique for crashworthiness design (Patel'07)
- **HCA = Cellular Automata (CA) + FEM**
- CAs are characterized by local interactions

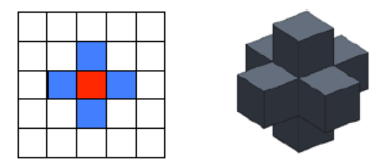
Global Formulation

$$
\begin{aligned}
\text{find} \quad & \underset{\sim}{x} \\
\text{s.t.} \quad & \underset{\sim}{h}(\underset{\sim}{x}) = \underset{\sim}{0} \\
& \underset{\sim}{g}(\underset{\sim}{x}) \le \underset{\sim}{0} \\
& \underset{\sim}{H}(\underset{\sim}{x}) = \underset{\sim}{0} \\
& \underset{\sim}{G}(\underset{\sim}{x}) \le \underset{\sim}{0} \\
& x_i \in \{0,1\}, \quad i = 1, \ldots, n,
\end{aligned}
$$

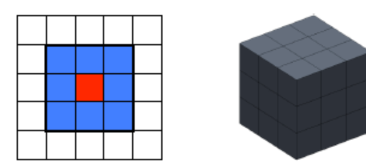
Local Formulation

$$
\begin{aligned}
\text{find} \quad & x_i \\
\text{s.t.} \quad & y_i(x_i) - y^* = 0 \\
& x_i \in \{0,1\},
\end{aligned}
$$

Neighborhoods



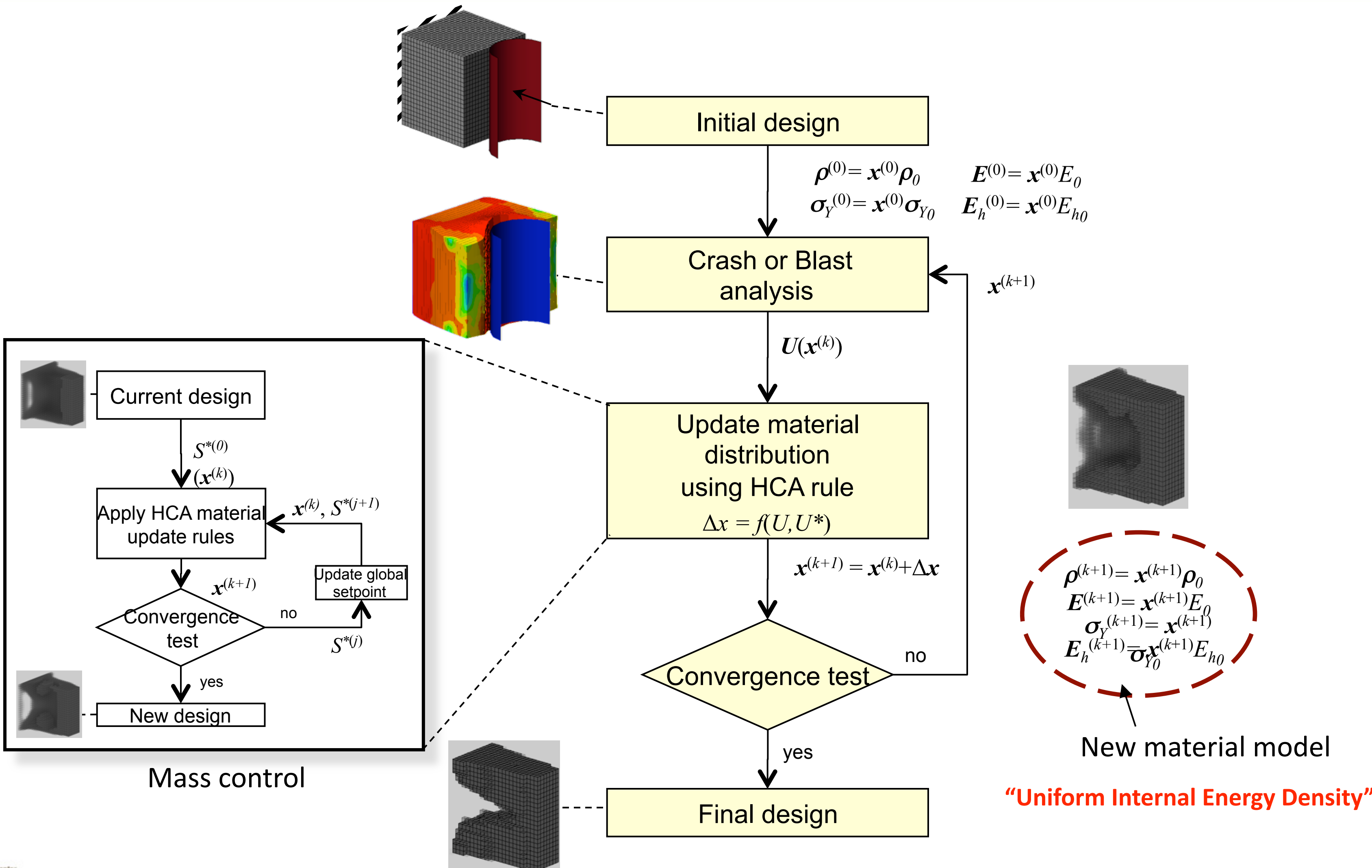
vonNeumann (2D: N=4, 3D: N=6)



Moore (2D: N=8, 3D: N=26)

Local CA rules and basic control theory is used to distribute material

HCA Overview: Algorithm

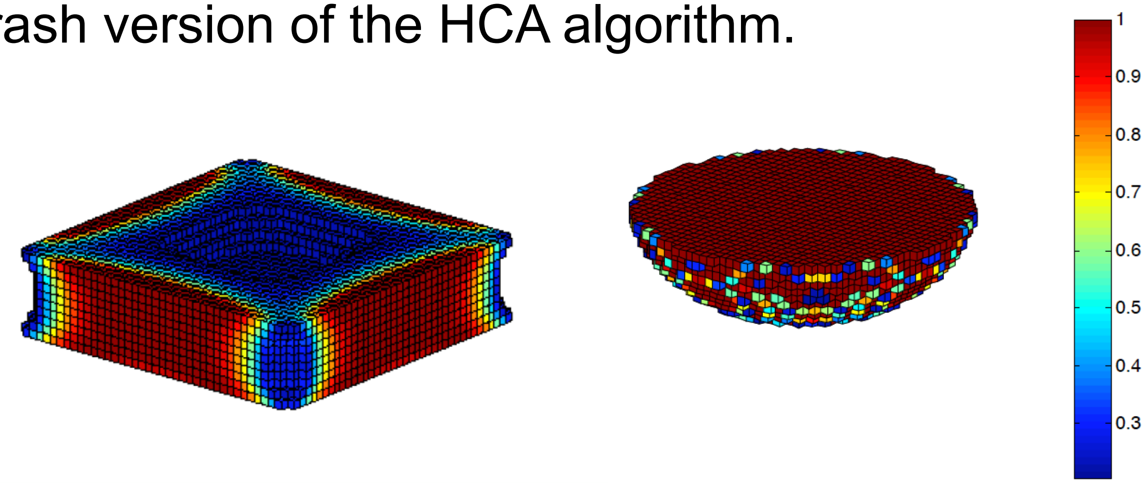


Modification of HCA for Blast: Field Variable Selection

- Field Variable:
  - Original crasHCA algorithm only utilized Internal Energy (IE) at the final time step
    - **IE at the final time is highly dependent on the simulation termination time**
    - Resulting topology is drastically different depending on the selected end time
  - Changed method for blast to use the IE at all time steps.

$$S_i = \int_{t=0}^{t=t_f} U_i(t)\, dt,$$

  - Will utilize the concept of a fully stressed design as implemented in the Crash version of the HCA algorithm.



Modification of HCA for Blast: Johnson-Cook Material Model

Material Card Selection

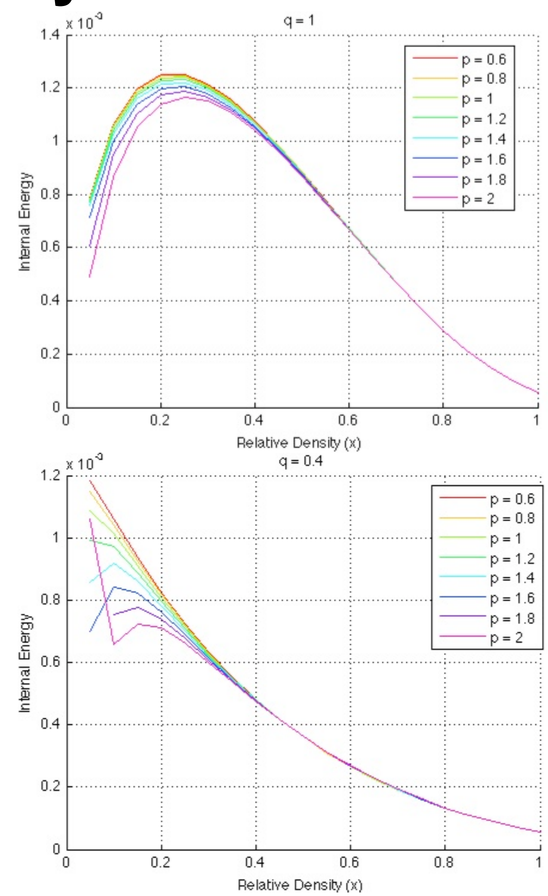
- Piecewise-linear elastic plastic material card:
  - Quasi-static
  - Hardening
  - Plastic deformation
- Johnson-Cook:
  - Can be used for dynamic loading situations
  - Strain rate effects
  - Temperature effects

$$E = E_0 x^p \text{ and } G = G_0 x^p$$

$$\sigma = [A + B\varepsilon^n][1 + C\ln\dot{\varepsilon}][1 - T^{*m}]$$

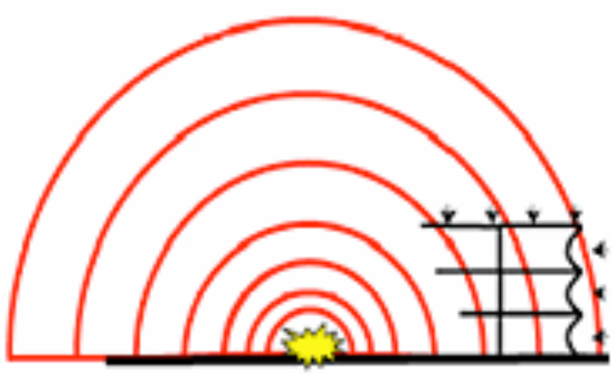
$$A = A_0 x^q, \quad B = B_0 x^q, \quad C = C_0 x^q$$

Johnson-Cook: Effect of density on Internal Energy



Modification of HCA for Blast: CONWEP Blast Model

- Load Type:
  - Began using the CONWEP algorithm for the blast model in the 3-D solid element HCA method.
    - Quick Analysis time (relative to MMALE)
    - Required minimal changes to the HCA algorithm
  - The objective is to design substructure that responds to a blast event in a desired manner. CONWEP can be used in this scenario since we are only looking at the response of a small piece of structure rather than the whole object.



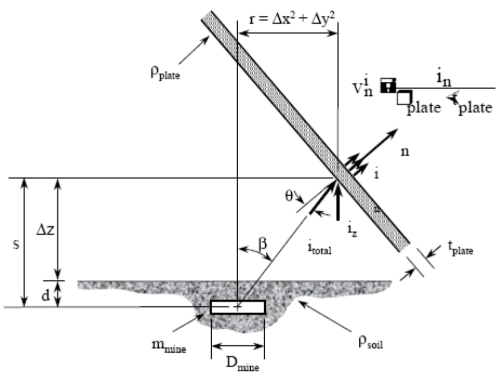
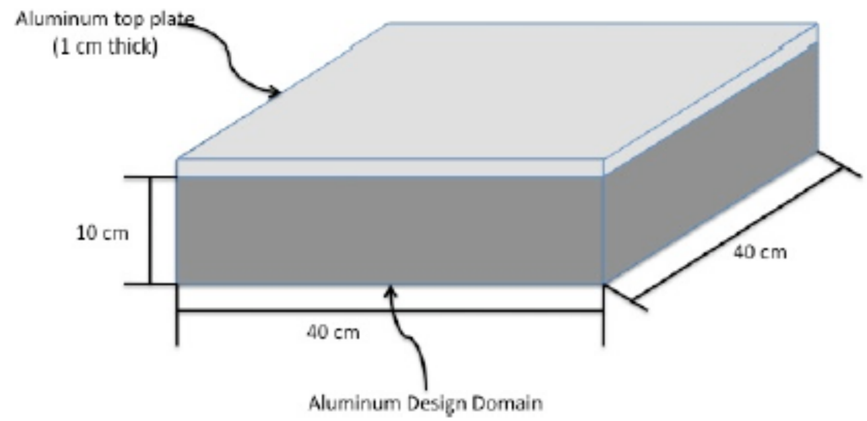


Figure 1. Definition of variables in the US Army TACOM Impulse Model (Adapted from Westine *et al.*, 1985).

Implementation

As a proof of concept, a rectangular design domain was created to represent a piece of armor.

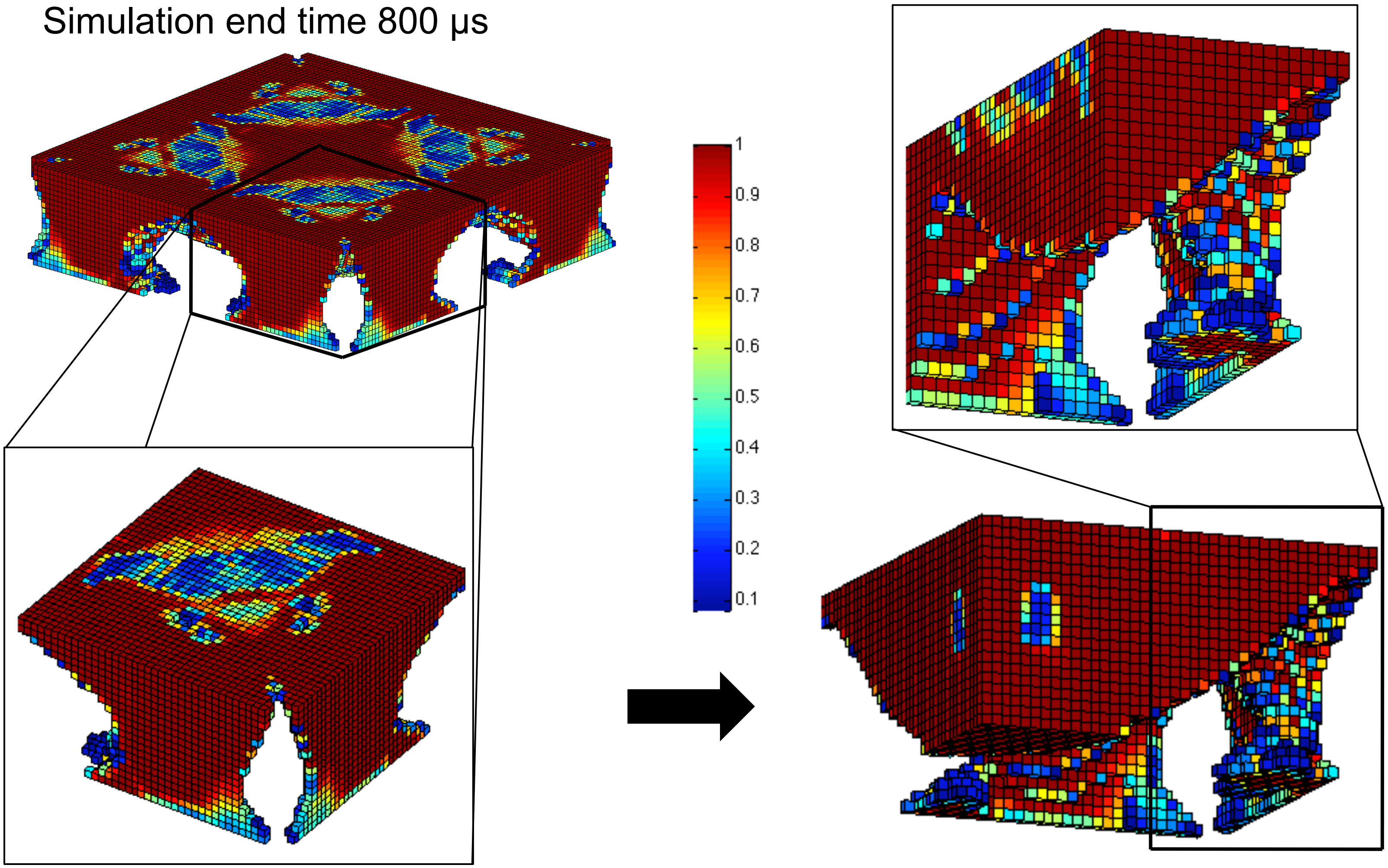
- Design domain is 40 x 40 x 10 cm aluminum (represents armor substructure)
- Top layer is 40 x 40 x 1 cm ceramic (represents ceramic top plate)
- Domain and top plate have fixed x, y, and z displacement boundary conditions on all sides.
- Blast is positioned 100 cm up from origin (89 cm from top center of plate)
- Hourglass control is included to help prevent complex sound speeds arising in low density elements
- The target mass is set to be 50% of a full design domain



- Generated Topology to be compared against a baseline model that is full density, but half as thick.
- The top of the baseline design will be 94 cm from the blast source (i.e. the base of the domain will be the same distance in both cases)

Results: Integrated IE Objective

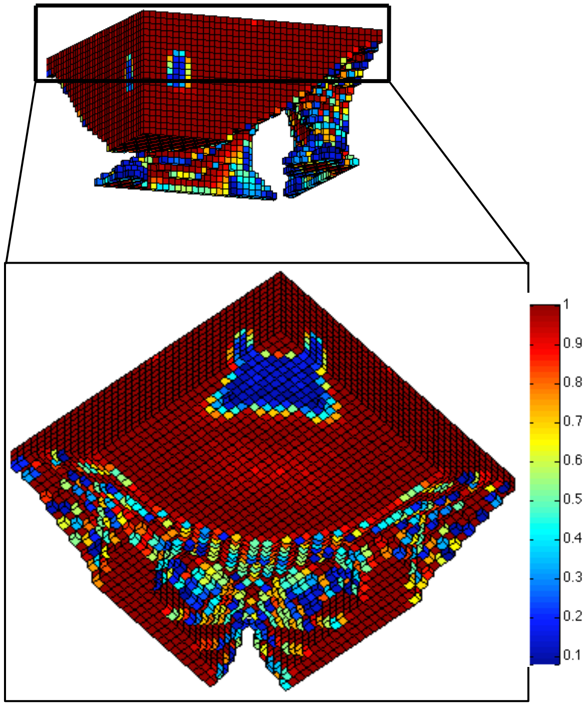
- Model mesh size to 0.5 cm (a symmetric quarter of the domain was run)
- Simulation end time 800 μs

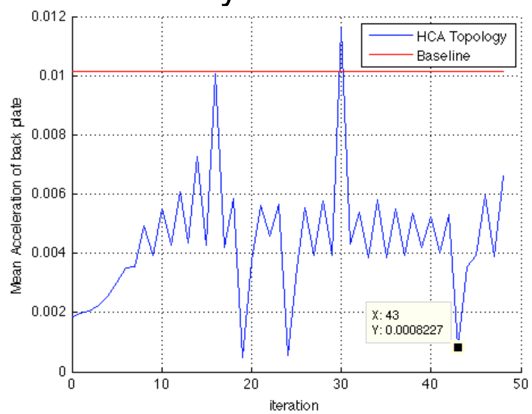


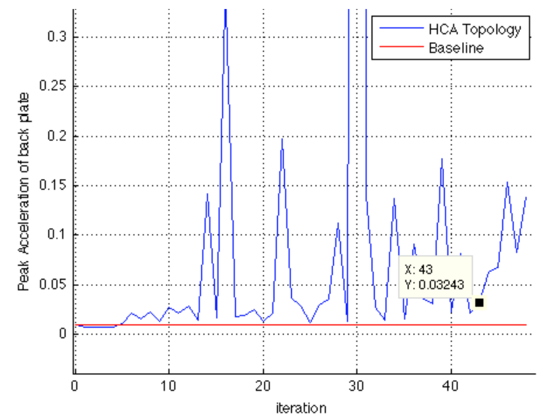
Results: Integrated IE Objective

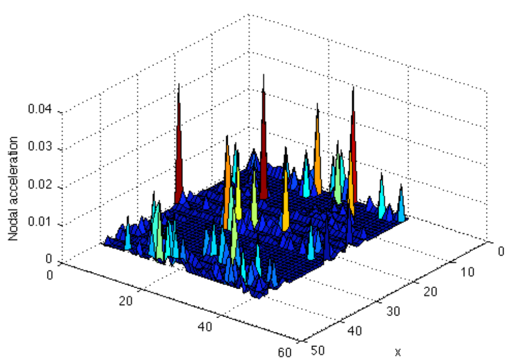
MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

- Resulting topology has mass where it would be expected and satisfies the mass target constraint.
- There is an order of magnitude improvement in the mean nodal acceleration of the bottom of the design domain versus the baseline case.
- Peak acceleration is misleading because of nodes that are being unrealistically accelerated relative to their neighbors

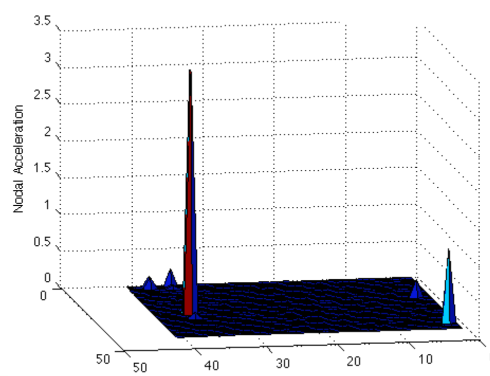








Acceleration Profile of iteration 43



Acceleration Profile of iteration 30

Final Remarks

- This investigation showed that the HCA algorithm could be modified to produce topologies that help to mitigate the acceleration transferred to the occupant from a blast loading
- Future work:
  - Investigate further the use of IE as the field variable in the optimization process
  - Investigation of other field variables to drive the optimization that are more appropriately related to acceleration
  - Mesh refinement study
  - Continued work to improve convergence and to mitigate errors in the LS-DYNA runs (i.e. complex sound speeds arising in low density elements)

Renaud, J.E., et. al. "Topology Sizing Optimization of Shell-based Structures for Crashworthiness Design using Hybrid Cellular Automata", *Journal of Mechanical Design*, 2009 (in review).

Questions?

Acknowledgments:
This research was performed under government contract from the US Army TARDEC, through a subcontract with Mississippi State University, for the Simulation Based Reliability and Safety (SimBRS) research program.

Backup

Verification of Monotonic Relationship between SED and Mass Density

MODELING AND SIMULATION, TESTING AND VALIDATION

- The Piecewise-linear elastic-plastic model was shown by Dr. Patel[1] to have a monotonic relationship between SED and mass density under the SIMP penalization method
- A similar study was conducted to determine if penalizing the Johnson-Cook model also yielded a monotonic relationship between SED and mass density.
  - Setup as a single solid LS-DYNA cube element under a rapid fixed loading
  - Mass and penalization factors are varied.

- As in the standard SIMP scheme, elastic modulus (and shear modulus) is penalized according to:

$$E = E_0 x^p \text{ and } G = G_0 x^p$$

- Johnson-Cook model calculates a von-mises flow stress according to:

$$\sigma = [A + B\varepsilon^n][1 + C\ln\dot{\varepsilon}][1 - T^{*m}]$$

- Penalizing this von-mises flow stress is akin to penalizing the yield stress. This is done by penalizing the parameters *A*, *B*,and *C.*

1. Patel, N.M., B.S. Kang, J.E. Renaud& A. Tovar. Crashworthiness design using topology optimization. ASME Journal of Mechanical Design. Accepted for publication: December 2008

Johnson-Cook Material Model: Penalization

- As in the standard SIMP scheme, elastic modulus (and shear modulus) is penalized according to:

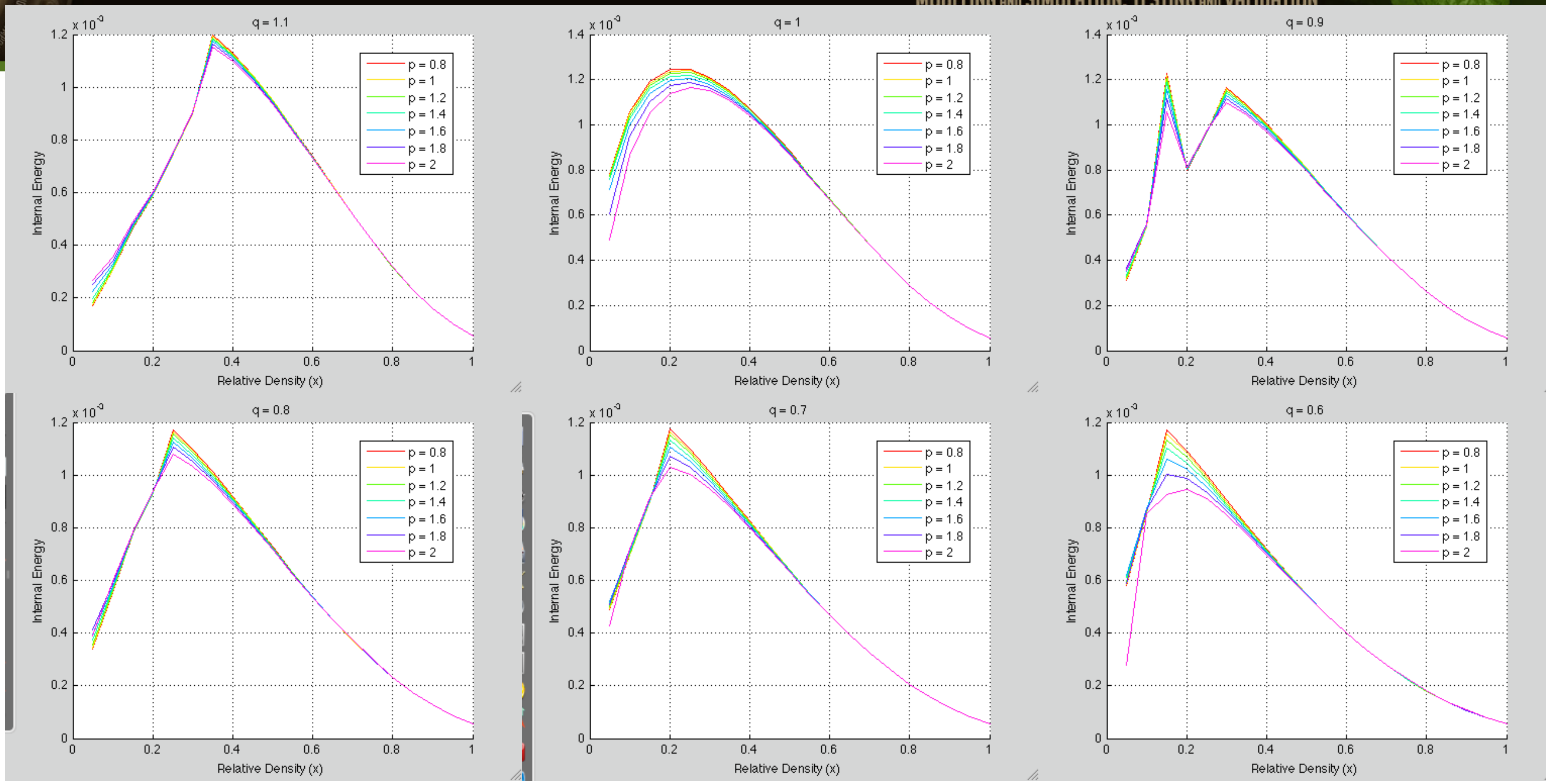
$$E = E_0 x^p \text{ and } G = G_0 x^p$$

- The Johnson-Cook model calculates a von-mises flow stress according to.

$$\sigma = [A + B\varepsilon^n][1 + C\ln\dot{\varepsilon}][1 - T^{*m}]$$

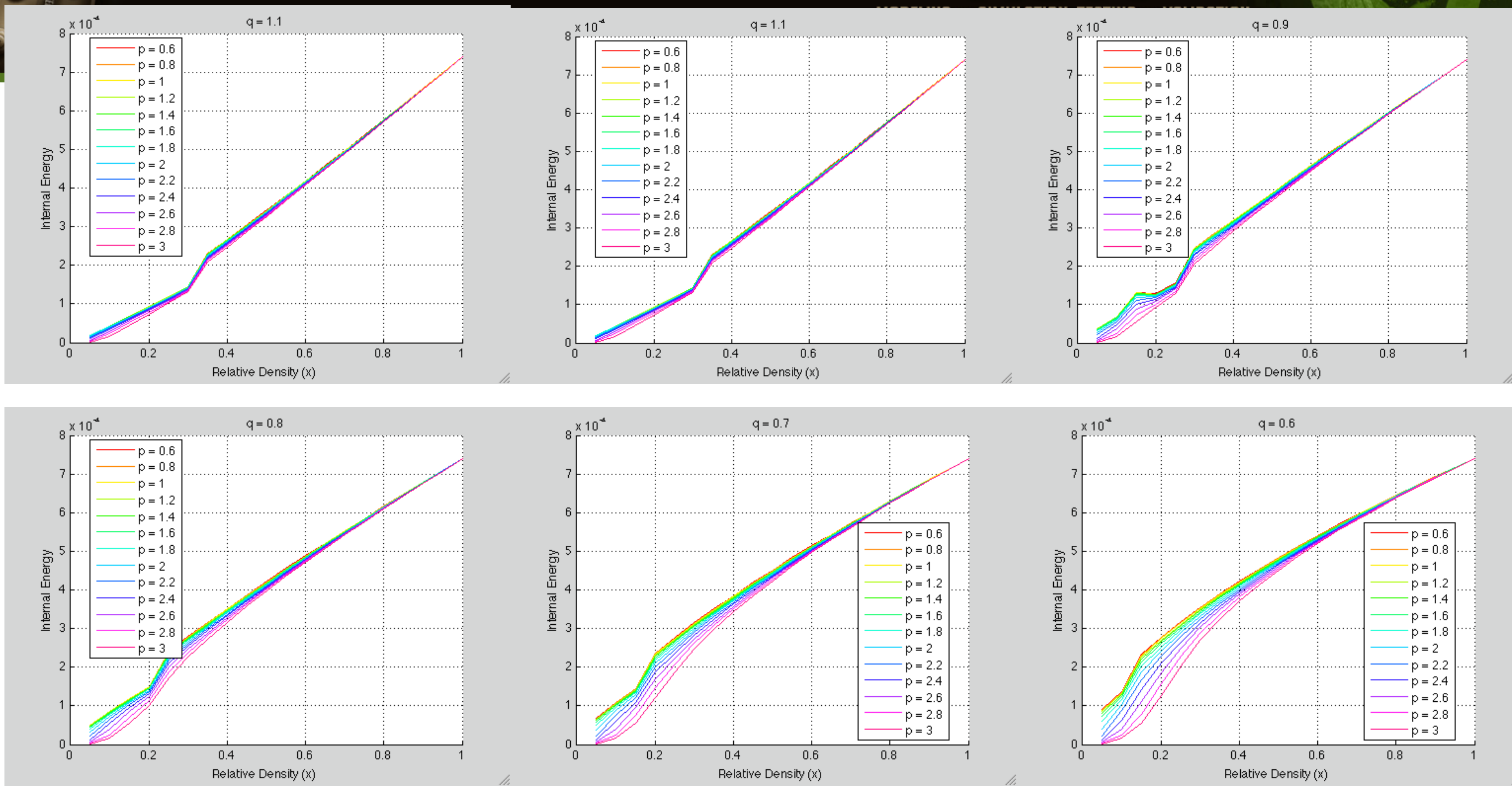
- Penalizing this von-mises flow stress is akin to penalizing the yield stress. This is done by penalizing the parameters *A*, *B*,and *C.*

Johnson-Cook Material Model: Fixed Load



- Under a constant load, the material does not behave monotonically under any penalization scheme
- Depending on choice of p and q, we may have to significantly increase the minimum density allowed in the CA and FE models

Johnson-Cook Material Model: Fixed Displacement



- Under fixed displacement the IED appears to have a monotonic relationship with relative density
- Blast loadings, however, are not fixed displacement problems.

Modification of HCA for Blast: CONWEP Blast Model

- CONWEP blast model: Load-Blast function in Ls-Dyna, is an implementation of the hemispherical blast models of Kingery and Bulmash.
- Empirical blast-loading model rather than explicitly simulating the progress of the shock wave from the high explosive through the air and its interaction with the structure
- Does not account for pressure confinement properties provided by imbedding explosive charge in soil.
- Scaling charge sizes for better agreement accepted, but applications to complete structures limited due to improperly modeled load distributions
- More complex structures and interaction of detonation products and debris requires a more sophisticated fluid structure formulation.

$$P(\tau) = P_r \cdot \cos^2\theta + P_i \cdot (1 + \cos^2\theta - 2\cos\theta)$$

Kingery, C. N., and G. Bulmash. "Air-Blast Parameters from TNT Spherical Air Burst and Hemispherical Surface Burst." ARBRL-TR-02555, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1984

Department of the Army. "Fundamentals of Protective Design for Conventional Weapons." TM 5-855-1, Washington, D.C., November 1986.

Agenda

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

- Introduction
- Overview of Hybrid Cellular Automata (HCA)
- Methodology
  - Field Variable
  - Material Model
  - Blast Model
- Implementation
- Results